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ROBUST NETWORK DESIGN - CONNECTIVITY AND BEYOND

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14. ABSTRACT

One of the prevailing needs of the U.S. Air Force has been to utilize a heterogeneous set of physical links (RF, Optical/Laser and SATCOM), for interconnecting a set of terrestrial, space and highly mobile airborne platforms (satellites, aircrafts and Unmanned Aerial Vehicles (UAVs)) to form an Airborne Network (AN). Not only does this complex network involve a large set of heterogeneous resources, but also the operative environment of this network is highly dynamic. Thus, there has been a demand for new models to characterize, manage and quantify network performance under such diverse network operating conditions. The goal of this research project was to undertake an investigation into some of the fundamental issues underlying this operative environment that is essential for successful design, deployment and operation of such a complex network. In this respect, studies were conducted in the following four key interrelated topics: (i) the design of mobility patterns of airborne platforms to provide stable operating conditions, (ii) the design of networks that enable graceful performance degradation, (iii) the information transfer capacity of a dynamic heterogeneous airborne network, and (iv) routing performance in diverse network conditions.

15. SUBJECT TERMS

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I. PROJECT BACKGROUND – GOALS OF THE PROJECT

One of the prevailing needs of the U.S. Air Force has been to utilize a heterogeneous set of physical links (RF, Optical/Laser and SATCOM), for interconnecting a set of terrestrial, space and highly mobile airborne platforms (satellites, aircrafts and Unmanned Aerial Vehicles (UAVs)) to form an Airborne Network (AN). Not only does this complex network involve a large set of heterogeneous resources, but also the operative environment of this network is highly dynamic. Thus, there has been a demand for new models to characterize, manage and quantify network performance under such diverse network operating conditions. The goal of this research project was to undertake an investigation into some of the fundamental issues underlying this operative environment that is essential for successful design, deployment and operation of such a complex network. In this respect, studies were conducted in the following four key interrelated topics:

- the design of mobility patterns of airborne platforms to provide stable operating conditions,
- the design of networks that enable graceful performance degradation,
- the information transfer capacity of a dynamic heterogeneous airborne network,
- routing performance in diverse network conditions.

A distinguishing feature of our project has been the analysis of the behavior of the network not only when it is connected, but also when it gets disconnected. This feature is critical for disruption-tolerant (or delay-tolerant) function of Airborne Networks, as it may not be possible to ensure that the network remains connected at all times. The proposed designs in this study ensure that the components of the disconnected network continue to perform as best as they can under disruptive circumstances, resulting in a graceful degradation of performance of the entire network.

This project also focused on the study of topology formation of Airborne Networks, and Distributed Storage Systems: In the course of the project we developed techniques that enable the network formed by the Airborne Networking Platforms (ANPs) to be connected at all times, even though the ANPs may move at high speeds. Techniques were developed for complete radio coverage of a flight corridor, thorough which combat aircrafts may be deployed to their missions. Routing algorithms for ANPs were developed that result in minimal amount of disruption caused by topology changes of the network. In a distributed storage system environment, nodes are susceptible to failure over time necessitating a repair mechanism to maintain a desired level of

system reliability. Regenerating Codes can be used to achieve such levels of reliability. In this regard, our research focused on two tracks: (i) we investigated the existence of exact regenerating codes where an exact copy of the lost data is regenerated when repairing the system, and (ii) in order to provide security against intruders, we characterized the maximum amount of information that can be stored safely on a system, and provided explicit schemes for protecting a system.

At the final stage of the project we have made significant progress in our stated objectives and approximately thirty technical papers dealing with issues related to the above outlined objectives have already been published, or scheduled to be published.

II. Summary Of Findings under the Project

In keeping with the goal of this research effort to ensure *network integrity* as well as *data integrity,* the project's research thrust was divided into two directions – one to ensure network integrity and the other to ensure data integrity. In the following we summarize our research findings in these two areas. Research findings in the network integrity part are summarized in subsections IIA, IIB, and the data integrity part in subsections IIC, IID, IIE and IIF.

II.A. Resource Efficient Backbone Network design in Fault-free Scenario

Prior to our research effort, Airborne Network research was primarily directed towards Mobile Ad-hoc Networks (MANET). From our experience in design and implementation of an Army Research Office funded research project on MANET, we argued that a MANET formed by Airborne Networking Platforms (small/large airplanes, drones) may not be as reliable as needed in a military operational scenario. We argued for creation of a *backbone network* with the ANPs wherever possible so that they can provide communication support to the aircrafts flying to accomplish a mission. A major part of our research effort was directed towards creation of a resource efficient backbone network that provides communication support to the aircrafts on a mission. We assumed that the aircrafts on a mission fly through a preplanned *air corridor*. The goal of the backbone network design was to make sure that (i) the air-corridor has radio coverage at all times and (ii) the backbone network formed by the ANPs remains connected at all times. Both of these problems are challenging due to the mobility of the ANPs, the radio coverage area changes with time, as does the topology of the backbone network over time. In fact, the goal of our effort was to extract time invariant property out of a time varying network. In our research we designed algorithms to find the (i) fewest number of ANPs that could provide radio coverage to the air corridor at all times and (ii) critical transmission range needed by the ANPs so that the resulting backbone remains connected at all times (i.e., the entire duration of the operation).

II.B. Resource Efficient Backbone Network design in Faulty Scenario

We considered a scenario where a part of the backbone network may not be operational due to an enemy attack or jamming. We introduced the notion of *region-based faults*, where the faults are confined to a region. The regions can be defined in the geometric space or in the topological space. In our research we designed algorithms to find the critical transmission range needed by the ANPs so that even after failure of some or all of the network equipment in a certain region (due to an enemy attack), the surviving part of the backbone network remains connected and is able to carry out it functionality under a degraded condition for the remaining duration of the operation.

II.C. Backbone Network Operation in Delay-Tolerant Mode

A part of our effort in IIA and IIB was directed towards computation of the critical transmission range needed by the ANPs so that the resulting backbone remains connected, both for the fault-free and faulty scenario. Suppose that our computation shows that the minimum transmission range needed by the ANPs to have a connected network at all times is τ. However, it is possible that the maximum transmission range of some of the ANPs is υ, where $\upsilon < \tau$. This will imply that the Backbone Network will not be connected at all times and hence at times, it may have to operate in a disconnected mode. If a large file has to be transferred from a node *u* to a node *v* in the network, a part of the file may have wait in an intermediate node *w* for a period of time, before it is forwarded to the next node on the path from *u* to *v*. As part of this project we have developed algorithms that ensure that the file will be transferred from the source node to the destination node in the fastest possible time, even if the file has to wait at some intermediate nodes, due to unavailability of the link to the next node on the path.

II.D. Operation in Contested Airspace where Backbone Network is Infeasible

In a contested airspace, a backbone network may be infeasible as it will most likely be attacked by the enemy. If a backbone network is infeasible, then the Airborne Network has to operate as a MANET. As a part of our effort, we have also developed algorithms to compute the critical transmission range needed by the aircrafts to keep the resulting network connected, even when the aircrafts are flying with unpredictable flight path in the deployment area.

II.E. Fast and Efficient Data Reconstruction in Distributed Storage Systems

We were able to design a new erasure-coded storage system that reduces both network traffic and disk I/O by around 25% to 45% during reconstruction of missing or otherwise unavailable data, with no additional storage, the same fault tolerance, and arbitrary flexibility in the choice of parameters, as compared to common distributed storage systems. It is based on novel encoding and decoding techniques. We tested the new system in Facebook's warehouse datacenters and observed a 36% reduction in the computation time and a 32% reduction in the data read time, in addition to the 35% reduction in network traffic and disk IO. We were also able to reduce the latency of degraded reads and perform faster recovery from failed or decommissioned machines.

- K. V. Rashmi, Nihar B. Shah, Dikang Gu, Hairong Kuang, Dhruba Borthakur, and Kannan Ramchandran, "A "Hitchhiker's" Guide to Fast and Efficient Data Reconstruction in Erasure-coded Data Centers", ACM SIGCOMM, Aug 2014.
- K. V. Rashmi, Nihar B. Shah and Kannan Ramchandran, "A Piggybacking Design Framework for Read- and Download-efficient Distributed Storage Codes", IEEE International Symposium on Information Theory (ISIT), Istanbul, Jul. 2013.

II.F. Design and Analysis of Data Access Protocol in Distributed Storage Systems

While the use of codes for providing improved security and integrity of data in distributed storage systems, how fast such systems can provide data or how we should optimize data access protocols are not studied. We first studied data access performance of data storage systems based on codes through the lens of queueing theory, and analytically characterized the latency performance of distributed storage systems. Then, we designed superior data access protocol, which uses redundant requests to improve data access performance.

- Nihar B. Shah, Kangwook Lee and Kannan Ramchandran, "The MDS Queue: Analysing Latency Performance of Codes", ISIT 2014.

- Nihar B. Shah, Kangwook Lee and Kannan Ramchandran, "When Do Redundant Requests Reduce Latency?", Allerton Conference on Control, Computing and Communication, Urbana-Champaign, Oct. 2013.

II.G. PRIVACY-AWARE INFORMATION RETRIEVAL AND SHARING

We want to retrieve data from a public database without revealing to the server which record is being retrieved. We proposed new systems where one can retrieve data from coded distributed database systems. Moreover, we also designed systems where one can search database by providing multimedia data such as voices, faces, or locations instead of textual descriptions. We also studied how we can share private information across a network with low communication cost. With our proposed distributed algorithm, one can share secrets across a general network without worrying about reveal your secret.

- Nihar B. Shah, K. V. Rashmi and Kannan Ramchandran, "One Extra Bit of Download Ensures Perfectly Private Information Retrieval", ISIT 2014.
- Giulia Fanti, Matthieu Finiasz, Gerald Friedland, Kannan Ramchandran, "Toward efficient, privacy-aware media classification on public databases", Proceedings of ACM International Conference of Multimedia Retrieval (ICMR), April 2014
- Nihar B. Shah, K. V. Rashmi and Kannan Ramchandran, "Secret Sharing Across a Network with Low Communication Cost: Distributed Algorithm and Bounds", IEEE International Symposium on Information Theory (ISIT), Istanbul, Jul. 2013.

III. TRAINING & PROFESSIONAL DEVELOPMENT OPPORTUNITIES PROVIDED

As a part of this project, several PhD students at the two participating universities have been trained in the design of robust and resilient networks in presence of faults. One student who was deeply involved in the project from its inception, successfully defended her PhD dissertation in May 2014. In addition, two post-docs, one at University of California, Berkeley and the other at Arizona State University have actively participated in the project and thereby trained through this research effort.

IV. RESULTS DISSEMINATION

The results have been disseminated in the scientific community through publications in scientific journals and presentations at conferences. In addition, the PIs of this project have given several invited talks at other research universities, such as the Kings College in London, and industrial research laboratories, such as Deutsche Telekom in Berlin, Germany.

V. PUBLICATION LIST

1. S. Shirazipourazad, A. Sen, S. Bandyopadhyay, Fault-tolerant Design of Wireless Sensor Networks with Directional Antennas, to appear in Pervasive and Mobile Computing (PMC) Journal 2014.
2. A. Mazumder, A. Das, C. Zhou, A. Sen, Region-based Fault-tolerant Distributed File Storage System Design Under Budget Constraint, International Workshop on Reliable Networks Design and Modeling (RNDM) IEEE, Barcelona, Spain, November 2014. **Best paper award.**
3. A. Mazumder, C. Zhou, A. Das, A. Sen, Progressive Recovery from Failure in Multi-layered Interdependent Network Using a New Model of Interdependency, International Conference on Critical Information Infrastructures Security (CRITIS), Limassol, Cyprus, October, 2014.
4. A. Das, A. Banerjee, A. Sen, Root Cause Analysis of Failures in Interdependent Power-Communication Networks, IEEE Military Communications Conference (MILCOM), Baltimore, Maryland, October 2014.

5. C. Zhou, A Mazumder, A. Sen, M. Reisslein and A. Richa, On Shortest Single/Multiple Path Computation Problems in Fiber-Wireless (FiWi) Access Networks, 15th IEEE International Conference on High Performance Switching and Routing, Vancouver, Canada in July 2014.
6. A. Sen, A. Mazumder, J. Banerjee, A. Das, and R. Compton, Identification of K Most Vulnerable Nodes in a Multi-layered Network Using a New Model of Interdependency, 6th IEEE International Workshop on Network Science for Communication Networks, held in conjunction with IEEE Infocom in Toronto, Canada, May 2014
7. S. Banerjee, A. Das, A. Mazumder, Z. Derakhshandeh, A. Sen, On the Impact of Coding Parameters on Storage Requirement of Region-based Fault Tolerant Distributed File System Design, IEEE International Conference on Computing, Networking and Communications (ICNC) IEEE, Honolulu, Hawaii, January 2014.
8. A. Mazumder, A. Das, S. Gokalp, N. Kim, A. Sen, H. Davulcu, Spatio-Temporal Signal Recovery from Political Tweets in Indonesia , International Conference on Social Computing (SocialCom) ASE/IEEE, Washington, D.C., September 2013.
9. S. Shirazipourazad, C. Zhou, Z. Derakhshandeh, A. Sen, Analysis of On-line Routing and Spectrum Allocation in Spectrum-sliced Optical Networks, IEEE International Communication Conference (ICC), Budapest, Hungary, June 2013.
10. S. Shirazipourazad, C. Zhou, Z. Derakhshandeh, A. Sen, On Routing and Spectrum Allocation in Spectrum-sliced Optical Networks, IEEE Infocom Mini-Conference, Torino, Italy, April, 2013.
11. S. Shirazipourazad, A. Sen, S. Bandyopadhyay, Fault-tolerant Design of Wireless Sensor Networks with Directional Antennas, International Conference on Distributed Computing and Networking (ICDCN) 2013. **Best paper award**.
12. S. Banerjee, S. Shirazipourazad and A. Sen, On Region-based Fault Tolerant Design of Distributed File Storage in Networks, IEEE INFOCOM (Mini-Conference), Orlando, USA, 2012.
13. S. Shirazipourazad, P. Ghosh and A. Sen, On Connectivity of Airborne Networks with Unpredictable Flight Path of Aircrafts, ACM MobiHoc Workshop on Airborne Networks and Communications, Hilton Head Island, SC, 2012.
14. S. Shirazipourazad, B. Bogard, H. Vachhani, A. Sen and P. Horn, Influence Propagation in Adversarial Setting: How to Defeat Competition with Least Amount of Investment, in Proceedings of the 21st ACM International Conference on Information and Knowledge Management (CIKM), Maui, HI, USA, 2012.
15. S. Shirazipourazad, P. Ghosh and A. Sen, "On Connectivity of Airborne Networks in Presence of Region-based Faults", IEEE Milcom, Military Communications Conference, Baltimore, MD, 2011.
16. S. Banerjee , S. Shirazipourazad, P. Ghosh and A. Sen, "Beyond Connectivity - New Metrics to Evaluate Robustness of Networks", IEEE Conference on High Performance Switching and Routing (HPSR), Cartagena, Spain, 2011.
17. S. Banerjee, S. Shirazipourazad and A. Sen, "Design and Analysis of Networks with Large Components in Presence of Region-Based Faults" IEEE International Conference on Communication, Kyoto, Japan, 2011.
18. S. Banerjee and A. Sen, Impact of Region-Based Faults on the Connectivity of Wireless Networks in Log-normal Shadow Fading Model "IEEE International Conference on Communication , Kyoto, Japan, 2011.
19. S. Banerjee, S. Murthy and A. Sen, "On a Fault-tolerant Resource Allocation Scheme for Revenue Maximization in Data Centers", in IEEE ANTS, 2011.
20. A. Sen and S. Banerjee, "Impact of Region-based Faults on the Connectivity and Capacity of Wireless Networks, (Invited Paper), *47th Annual Allerton Conference on Communication, Control, and Computing*, University of Illinois, Urbana-Champaign, September 2009.

Under Review:

21. S. Banerjee, S. Shirazipourazad and A. Sen, "Design of Distributed Data Storage Networks Robust Against Region-Based Faults," IEEE Trans. on Networking.
22. A. Sen, S. Banerjee, B. H. Shen, L. Zhou, B. Hao, S. Murthy, "A New Evaluation Metric of Fault-tolerant Wireless Networks," IEEE Trans. on Networking.
23. S. Shirazipourazad, B. Bogard, H. Vachhani, A. Sen and P. Horn, "Influence Propagation in Adversarial Setting: How to Defeat Competition with Least Amount of Investment", Computational Social Networks (Springer)
24. S. Shirazipourazad, C. Zhou, Z. Derakhshandeh and A. Sen, "On Routing and Spectrum Allocation in Spectrum-sliced Optical Networks", IEEE Transactions on Networking
25. S. Shirazipourazad, P. Ghosh and A. Sen, "On Connectivity of Airborne Networks" AIAA Journal of Aerospace Information Systems (formerly known as Journal of Aerospace Computing, Information, and Communication)